

Measurement of the relative yields of $\psi(2S)$ to $\psi(1S)$ mesons produced at forward and backward rapidity in $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

A. Adare,¹³ C. Aidala,⁴⁰ N.N. Ajitanand,⁵⁶ Y. Akiba,^{51,52,*} M. Alfred,²² V. Andrieux,⁴⁰ K. Aoki,^{31,51} N. Apadula,^{27,57} H. Asano,^{34,51} C. Ayuso,⁴⁰ B. Azmoun,⁷ V. Babintsev,²³ M. Bai,⁶ N.S. Bandara,³⁹ B. Bannier,⁵⁷ K.N. Barish,⁸ S. Bathe,^{5,52} A. Bazilevsky,⁷ M. Beaumier,⁸ S. Beckman,¹³ R. Belmont,^{13,40} A. Berdnikov,⁵⁴ Y. Berdnikov,⁵⁴ D.S. Blau,³³ M. Boer,³⁶ J.S. Bok,⁴⁵ E.K. Bownes,⁴¹ K. Boyle,⁵² M.L. Brooks,³⁶ J. Bryslawskyj,^{5,8} V. Bumazhnov,²³ C. Butler,²⁰ S. Campbell,^{14,27} C. CanoaRoman,⁵⁷ R. Cervantes,⁵⁷ C.-H. Chen,⁵² C.Y. Chi,¹⁴ M. Chiu,⁷ I.J. Choi,²⁴ J.B. Choi,¹⁰ T. Chujo,⁶⁰ Z. Citron,⁶² M. Connors,^{20,52} N. Cronin,^{41,57} M. Csanád,¹⁷ T. Csörgő,^{30,63} T.W. Danley,⁴⁶ A. Datta,⁴⁴ M.S. Daugherty,¹ G. David,⁷ K. DeBlasio,⁴⁴ K. Dehmelt,⁵⁷ A. Denisov,²³ A. Deshpande,^{52,57} E.J. Desmond,⁷ A. Dion,⁵⁷ P.B. Diss,³⁸ D. Dixit,⁵⁷ J.H. Do,⁶⁴ A. Drees,⁵⁷ K.A. Drees,⁶ M. Dumancic,⁶² J.M. Durham,³⁶ A. Durum,²³ J.P. Dusing,⁴¹ T. Elder,^{20,30} A. Enokizono,^{51,53} H. En'yo,⁵¹ S. Esumi,⁶⁰ B. Fadem,⁴¹ W. Fan,⁵⁷ N. Feege,⁵⁷ D.E. Fields,⁴⁴ M. Finger,⁹ M. Finger, Jr.,⁹ S.L. Fokin,³³ J.E. Frantz,⁴⁶ A. Franz,⁷ A.D. Frawley,¹⁹ Y. Fukuda,⁶⁰ C. Gal,⁵⁷ P. Gallus,¹⁵ P. Garg,³ H. Ge,⁵⁷ F. Giordano,²⁴ A. Glenn,³⁵ Y. Goto,^{51,52} N. Grau,² S.V. Greene,⁶¹ M. Grosse Perdekamp,²⁴ T. Gunji,¹² H. Guragain,²⁰ T. Hachiya,^{51,52} J.S. Haggerty,⁷ K.I. Hahn,¹⁸ H. Hamagaki,¹² H.F. Hamilton,¹ S.Y. Han,¹⁸ J. Hanks,⁵⁷ S. Hasegawa,²⁸ T.O.S. Haseler,²⁰ K. Hashimoto,^{51,53} X. He,²⁰ T.K. Hemmick,⁵⁷ J.C. Hill,²⁷ K. Hill,¹³ R.S. Hollis,⁸ K. Homma,²¹ B. Hong,³² T. Hoshino,²¹ N. Hotvedt,²⁷ J. Huang,⁷ S. Huang,⁶¹ K. Imai,²⁸ M. Inaba,⁶⁰ A. Iordanova,⁸ D. Isenhower,¹ Y. Ito,⁴² D. Ivanishchev,⁵⁰ B.V. Jacak,⁵⁷ M. Jezghani,²⁰ Z. Ji,⁵⁷ J. Jia,^{7,56} X. Jiang,³⁶ B.M. Johnson,^{7,20} V. Jorjadze,⁵⁷ D. Jouan,⁴⁸ D.S. Jumper,²⁴ S. Kanda,¹² J.H. Kang,⁶⁴ D. Kapukchyan,⁸ E. Karthas,⁵⁷ D. Kawall,³⁹ A.V. Kazantsev,³³ J.A. Key,⁴⁴ V. Khachatryan,⁵⁷ A. Khanzadeev,⁵⁰ C. Kim,^{8,32} D.J. Kim,²⁹ E.-J. Kim,¹⁰ G.W. Kim,¹⁸ M. Kim,^{32,55} M.L. Kimball,¹ B. Kimelman,⁴¹ D. Kincses,¹⁷ E. Kistenev,⁷ R. Kitamura,¹² J. Klatsky,¹⁹ D. Kleinjan,⁸ P. Kline,⁵⁷ T. Koblesky,¹³ B. Komkov,⁵⁰ J.R. Kotler,⁴¹ D. Kotov,^{50,54} S. Kudo,⁶⁰ K. Kurita,⁵³ M. Kurosawa,^{51,52} Y. Kwon,⁶⁴ R. Lacey,⁵⁶ J.G. Lajoie,²⁷ E.O. Lallow,⁴¹ A. Lebedev,²⁷ S. Lee,⁶⁴ S.H. Lee,⁵⁷ M.J. Leitch,³⁶ Y.H. Leung,⁵⁷ N.A. Lewis,⁴⁰ X. Li,^{11,36} S.H. Lim,^{36,64} L. D. Liu,⁴⁹ M.X. Liu,³⁶ V-R Loggins,²⁴ V.-R. Loggins,²⁴ K. Lovasz,¹⁶ D. Lynch,⁷ T. Majoros,¹⁶ Y.I. Makdisi,⁶ M. Makek,⁶⁵ M. Malaev,⁵⁰ A. Manion,⁵⁷ V.I. Manko,³³ E. Mannel,⁷ M. McCumber,³⁶ P.L. McGaughey,³⁶ D. McGlinchey,¹³ C. McKinney,²⁴ A. Meles,⁴⁵ A.R. Mendez,⁴¹ M. Mendoza,⁸ A.C. Mignerey,³⁸ D.E.M. Mihalik,⁵⁷ A. Milov,⁶² D.K. Mishra,⁴ J.T. Mitchell,⁷ G. Mitsuka,⁵² S. Miyasaka,^{51,59} S. Mizuno,^{51,60} A.K. Mohanty,⁴ P. Montuenga,²⁴ T. Moon,⁶⁴ D.P. Morrison,⁷ S.I.M. Morrow,⁶¹ T.V. Moukhanova,³³ T. Murakami,^{34,51} J. Murata,^{51,53} A. Mwai,⁵⁶ K. Nagai,⁵⁹ K. Nagashima,²¹ T. Nagashima,⁵³ J.L. Nagle,¹³ M.I. Nagy,¹⁷ I. Nakagawa,^{51,52} H. Nakagomi,^{51,60} K. Nakano,^{51,59} C. Nattress,⁵⁸ P.K. Netrakanti,⁴ T. Niida,⁶⁰ S. Nishimura,¹² R. Nouicer,^{7,52} T. Novák,^{30,63} N. Novitzky,^{29,57} R. Novotny,¹⁵ A.S. Nyanin,³³ E. O'Brien,⁷ C.A. Ogilvie,²⁷ J.D. Orjuela Koop,¹³ J.D. Osborn,⁴⁰ A. Oskarsson,³⁷ G.J. Ottino,⁴⁴ K. Ozawa,³¹ R. Pak,⁷ V. Pantuev,²⁵ V. Papavassiliou,⁴⁵ J.S. Park,⁵⁵ S. Park,^{51,55} S.F. Pate,⁴⁵ M. Patel,²⁷ J.-C. Peng,²⁴ W. Peng,⁶¹ D.V. Perepelitsa,⁷ G.D.N. Perera,⁴⁵ D.Yu. Peressounko,³³ C.E. PerezLara,⁵⁷ J. Perry,²⁷ R. Petti,^{7,57} M. Phipps,^{7,24} C. Pinkenburg,⁷ R. Pinson,¹ R.P. Pisani,⁷ C.J. Press,⁴¹ A. Pun,⁴⁶ M.L. Purschke,⁷ J. Rak,²⁹ B.J. Ramson,⁴⁰ I. Ravinovich,⁶² K.F. Read,^{47,58} D. Reynolds,⁵⁶ V. Riabov,^{43,50} Y. Riabov,^{50,54} D. Richford,⁵ T. Rinn,²⁷ S.D. Rolnick,⁸ M. Rosati,²⁷ Z. Rowan,⁵ J.G. Rubin,⁴⁰ J. Runchey,²⁷ A.S. Safonov,⁵⁴ B. Sahlmueller,⁵⁷ N. Saito,³¹ T. Sakaguchi,⁷ H. Sako,²⁸ V. Samsonov,^{43,50} M. Sarsour,²⁰ K. Sato,⁶⁰ S. Sato,²⁸ B. Schaefer,⁶¹ B.K. Schmoll,⁵⁸ K. Sedgwick,⁸ R. Seidl,^{51,52} A. Sen,^{27,58} R. Seto,⁸ P. Sett,⁴ A. Sexton,³⁸ D. Sharma,⁵⁷ I. Shein,²³ T.-A. Shibata,^{51,59} K. Shigaki,²¹ M. Shimomura,^{27,42} T. Shioya,⁶⁰ P. Shukla,⁴ A. Sickles,^{7,24} C.L. Silva,³⁶ J.A. Silva,⁴¹ D. Silvermyr,^{37,47} B.K. Singh,³ C.P. Singh,³ V. Singh,³ M. Slunečka,⁹ K.L. Smith,¹⁹ M. Snowball,³⁶ R.A. Soltz,³⁵ W.E. Sondheim,³⁶ S.P. Sorensen,⁵⁸ I.V. Sourikova,⁷ P.W. Stankus,⁴⁷ M. Stepanov,^{39,†} H. Stien,¹ S.P. Stoll,⁷ T. Sugitate,²¹ A. Sukhanov,⁷ T. Sumita,⁵¹ J. Sun,⁵⁷ SS Syed,²⁰ J. Sziklai,⁶³ A. Takeda,⁴² A. Taketani,^{51,52} K. Tanida,^{28,52,55} M.J. Tannenbaum,⁷ S. Tarafdar,^{61,62} A. Taranenko,^{43,56} G. Tarnai,¹⁶ R. Tieulent,²⁰ A. Timilsina,²⁷ T. Todoroki,^{51,60} M. Tomášek,¹⁵ C.L. Towell,¹ R. Towell,¹ R.S. Towell,¹ I. Tserruya,⁶² Y. Ueda,²¹ B. Ujvari,¹⁶ H.W. van Hecke,³⁶ J. Velkovska,⁶¹ M. Virius,¹⁵ V. Vrba,^{15,26} N. Vukman,⁶⁵ X.R. Wang,^{45,52} Z. Wang,⁵ Y. Watanabe,^{51,52} Y.S. Watanabe,^{12,31} F. Wei,⁴⁵ A.S. White,⁴⁰ C.P. Wong,²⁰ C.L. Woody,⁷ M. Wysocki,⁴⁷ B. Xia,⁴⁶ C. Xu,⁴⁵ Q. Xu,⁶¹ L. Xue,²⁰ S. Yalcin,⁵⁷ Y.L. Yamaguchi,^{12,52,57} H. Yamamoto,⁶⁰ A. Yanovich,²³ J.H. Yoo,³² I. Yoon,⁵⁵ H. Yu,^{45,49} I.E. Yushmanov,³³ W.A. Zajc,¹⁴ A. Zelenski,⁶ S. Zhou,¹¹ and L. Zou⁸

(PHENIX Collaboration)

[†] Abilene Christian University, Abilene, Texas 79699, USA

- ²Department of Physics, Augustana University, Sioux Falls, South Dakota 57197, USA
³Department of Physics, Banaras Hindu University, Varanasi 221005, India
⁴Bhabha Atomic Research Centre, Bombay 400 085, India
⁵Baruch College, City University of New York, New York, New York, 10010 USA
⁶Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
⁷Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
⁸University of California-Riverside, Riverside, California 92521, USA
⁹Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic
¹⁰Chonbuk National University, Jeonju, 561-756, Korea
¹¹Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, P. R. China
¹²Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
¹³University of Colorado, Boulder, Colorado 80309, USA
¹⁴Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA
¹⁵Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
¹⁶Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
¹⁷ELTE, Eötvös Loránd University, H-1117 Budapest, Pázmány P. s. 1/A, Hungary
¹⁸Ewha Womans University, Seoul 120-750, Korea
¹⁹Florida State University, Tallahassee, Florida 32306, USA
²⁰Georgia State University, Atlanta, Georgia 30303, USA
²¹Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
²²Department of Physics and Astronomy, Howard University, Washington, DC 20059, USA
²³IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
²⁴University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
²⁵Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
²⁶Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
²⁷Iowa State University, Ames, Iowa 50011, USA
²⁸Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
²⁹Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland
³⁰Károly Róberts University College, H-3200 Gyöngyös, Mátrai út 36, Hungary
³¹KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
³²Korea University, Seoul, 136-701, Korea
³³National Research Center "Kurchatov Institute", Moscow, 123098 Russia
³⁴Kyoto University, Kyoto 606-8502, Japan
³⁵Lawrence Livermore National Laboratory, Livermore, California 94550, USA
³⁶Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
³⁷Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
³⁸University of Maryland, College Park, Maryland 20742, USA
³⁹Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA
⁴⁰Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
⁴¹Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA
⁴²Nara Women's University, Kita-uoya Nishi-machi Nara 630-8506, Japan
⁴³National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute, Moscow, 115409, Russia
⁴⁴University of New Mexico, Albuquerque, New Mexico 87131, USA
⁴⁵New Mexico State University, Las Cruces, New Mexico 88003, USA
⁴⁶Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA
⁴⁷Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
⁴⁸IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, BP1, F-91406, Orsay, France
⁴⁹Peking University, Beijing 100871, P. R. China
⁵⁰PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
⁵¹RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
⁵²RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
⁵³Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
⁵⁴Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia
⁵⁵Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
⁵⁶Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA
⁵⁷Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA
⁵⁸University of Tennessee, Knoxville, Tennessee 37996, USA
⁵⁹Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
⁶⁰Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
⁶¹Vanderbilt University, Nashville, Tennessee 37235, USA
⁶²Weizmann Institute, Rehovot 76100, Israel
⁶³Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences (Wigner RCP, RMKI) H-1525 Budapest 114, POBox 49, Budapest, Hungary

⁶⁴Yonsei University, IPAP, Seoul 120-749, Korea

⁶⁵University of Zagreb, Faculty of Science, Department of Physics, Bijenička 32, HR-10002 Zagreb, Croatia

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The PHENIX Collaboration has measured the ratio of the yields of $\psi(2S)$ to $\psi(1S)$ mesons produced in $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV over the forward and backward rapidity intervals $1.2 < |y| < 2.2$. We find that the ratio in $p+p$ collisions is consistent with measurements at other collision energies. In collisions with nuclei, we find that in the forward (p -going or ^3He -going) direction, the relative yield of $\psi(2S)$ mesons to $\psi(1S)$ mesons is consistent with the value measured in $p+p$ collisions. However, in the backward (nucleus-going) direction, the $\psi(2S)$ is preferentially suppressed by a factor of ~ 2 . This suppression is attributed in some models to breakup of the weakly-bound $\psi(2S)$ through final state interactions with comoving particles, which have a higher density in the nucleus-going direction. These breakup effects may compete with color screening in a deconfined quark-gluon plasma to produce sequential suppression of excited quarkonia states.

I. INTRODUCTION

The production of quark-antiquark bound states in nuclear collisions has long been studied for evidence of a phase transition between normal nuclear matter, where quarks and gluons are confined in hadrons, to a plasma phase where colored partons are deconfined. Early predictions of charmonium suppression as an unambiguous signature of deconfinement [1] have proven to be overly simplistic, as a variety of competing mechanisms have been identified which do not require color screening to disrupt bound state $q\bar{q}$ pair formation and hadronization. It is necessary to quantitatively account for these effects to correct interpretation of what the measurements of quarkonia suppression in nuclear collisions imply about the quantum-chromodynamics phase diagram.

The heavy charm and bottom quarks are of particular interest, as they are produced through hard processes that are calculable with perturbative quantum-chromodynamics techniques [2] and their bound states are accessible experimentally through decays to dileptons. Models of $c\bar{c}$ and $b\bar{b}$ bound state production generally factorize quarkonia production into two stages: first, the prompt initial heavy quark production via gluon fusion, and after a formation time τ_f , the mechanism leading to hadronization into the final color singlet state [3–5]. In collisions involving nuclei, the initial heavy quark production can be affected by modifications of the parton distribution functions [6], energy loss in the nucleus [7], and scattering with other partons [8]. Effects which may be of hydrodynamic origin are also present in small systems [9–11], and may further alter the heavy quark final state [12, 13]. If these flow effects are due to quark-gluon-plasma formation, the presence of deconfined colored partons can inhibit coalescence into a bound state or dissolve fully-formed bound states [14]. The fully-formed pair may also be broken up through interactions with comoving hadrons outside the nucleus [15, 16].

One way to isolate final-state effects is through studies of states with the same quark content but different binding energies, such as the charmonium states $\psi(1S)$ and $\psi(2S)$, with binding energies of ~ 640 and ~ 50 MeV, respectively [17]. Before the charmonium formation time $\tau_f \sim 0.15$ fm/c, the precursor state is thought to be the same and so any effects on the precursor are likely identical. While significant initial-state effects on open charm have been found at the Relativistic Heavy Ion Collider (RHIC) [18, 19], these should equally affect all charm pairs before projection onto a final state. Therefore any differences in the modification of $\psi(2S)$ and $\psi(1S)$ production are likely due to late time effects which are sensitive to differences in the fully-formed meson radius and binding energy.

Previous measurements of $\psi(2S)$ suppression in $p+A$ collisions by the E866/NuSea [20] and NA50 [21] experiments were found to be well explained by models based on the breakup of fully formed charmonium states inside the nucleus, which naturally leads to a larger effect on the $\psi(2S)$ due to its larger radius [22]. However, this model fails to reproduce data from $d+\text{Au}$ collisions at midrapidity at RHIC [23], where the higher beam energy and shorter nuclear crossing time means the $c\bar{c}$ pairs project onto their final states outside the nucleus [24]. Breakup mechanisms which occur after the formation time can however explain the different suppression. Measurements over different rapidity intervals in asymmetric collisions can simultaneously provide information on the evolution of the $c\bar{c}$ state in different hadronic environments. In the $p/d/{}^3\text{He}$ -going direction, there are relatively few produced particles, while in the A -going direction, there may be significant final state interactions between the quarkonia state and the higher number of comoving hadrons.

II. MEASUREMENTS

Here, we present measurements in 2015 of the relative yields of $\psi(2S)$ to $\psi(1S)$ mesons at forward and backward rapidity in $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. We find that the relative production rate of $\psi(2S)$ to $\psi(1S)$ mesons in $p+p$ col-

* PHENIX Spokesperson: akiba@rcf.rhic.bnl.gov

† Deceased

lisions is consistent with expectations from a modified color evaporation model of charmonium production [25]. In $p/{}^3\text{He}+A$ collisions, over the forward ($p/{}^3\text{He}$ -going) rapidity interval $1.2 < y < 2.2$ the relative production rates of the two states are consistent with what is found in $p+p$. However, over the backward (A -going) rapidity interval $-2.2 < y < -1.2$, the $\psi(2S)$ is preferentially more suppressed than the $\psi(1S)$ by a factor of ~ 2 , which is likely due to final state effects such as interactions with comoving hadrons.

Dimuons from $\psi(2S)$ and $\psi(1S)$ decays were measured with the PHENIX muon spectrometer, which comprises two arms covering the forward and backward rapidity intervals $1.2 < |y| < 2.2$ [26]. Muons considered in this analysis pass through a the forward vertex tracking detector (FVTX) [27], a hadron absorber with a thickness of ~ 10 interaction lengths, then through three multi-plane cathode strip tracking chambers which reside in a radial magnetic field. After the tracking chambers are more layers of absorbers and Iarocci tubes for muon identification, where tracks must penetrate at least 2.5 interaction lengths of additional steel absorber. The dimuon trigger used in this analysis records events which have two tracks in the same spectrometer arm that pass through all absorber material.

Previous PHENIX measurements were not able to resolve the smaller $\psi(2S)$ peak in the dimuon mass spectrum near the larger, broad $\psi(1S)$ peak (cf. [28, 29]). However, the introduction of the four silicon tracking layers of the FVTX in 2012 now allows a precise measurement of the pair opening angle to be made before the muons undergo multiple scattering in the absorber. The additional FVTX tracking improves the dimuon mass resolution and reduces combinatorial background from hadron decays, allowing separation of the two peaks.

III. RESULTS

The measured dimuon mass spectra from $p+p$, $p+\text{Al}$, $p+\text{Au}$, and ${}^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 1, with the a–d (e–h) plots showing data recorded in the South (North) PHENIX muon spectrometer arm. These distributions comprise peaks at the $\psi(1S)$ and $\psi(2S)$ masses (~ 3.1 and ~ 3.7 GeV/ c^2 , respectively) on top of correlated background from charm and bottom hadron decays and Drell-Yan pairs, plus combinatorial background from light meson decays and hadrons which are not stopped in the absorbers. The fits to the data are shown as a solid [black] line with a shaded [gray] band representing the 90% confidence level of the fit, with the resonances and total background components of the fit represented by dashed [blue] and dotted [red] lines, respectively.

The combinatorial background contribution is extracted using event mixing techniques and is normalized to match the like-sign background. To determine systematic uncertainties on the relative yields that vary from 1%

in $p+p$ collisions to 4% in ${}^3\text{He}+\text{Au}$ collisions, the mass range over which the normalization is done is varied from a nominal range of 2–5 GeV/ c^2 to 1.5–5 GeV/ c^2 and 2.5–5.5 GeV/ c^2 . The correlated background is modeled in the fit by an exponential.

The resonances are represented in the fit by the sum of a Crystal Ball function [30] plus a Gaussian. The Crystal Ball is a continuous piecewise function that comprises a Gaussian on the high mass side and an exponential on the low mass side, which accounts for tails due to muon energy loss straggling in the absorbers. The additional Gaussian is needed to account for tracks which have fewer than 14 hits out of a possible 16 in the muon tracker and therefore form pairs with poorer mass resolution. Based on an analysis of the mass resolution of pairs formed by these poorly reconstructed tracks, the width of this second Gaussian is set to 200 MeV/ c^2 (230 MeV/ c^2) for the $\psi(1S)$ ($\psi(2S)$) peak and varied by $\pm 25\%$ to determine a systematic uncertainty on the relative yields. This is the dominant source of systematic uncertainty on this measurement, and ranges from 8% in $p+p$ collisions to 37% in the Au-going direction in ${}^3\text{He}+\text{Au}$ collisions, due to the larger combinatorial background. The difference between the centers of the $\psi(2S)$ and $\psi(1S)$ peaks is set to the Particle Data Group value [31] of 0.589 MeV/ c^2 , and the width of the $\psi(2S)$ Crystal Ball function is set to 1.15 times the width of the $\psi(1S)$ peak, following expectations of the mass resolution in the muon spectrometer from simulations and previous measurements [32]. This constraint is varied from 1.1 to 1.2 times the $\psi(1S)$ width to determine a systematic uncertainty on the relative yields of $\sim 3\%$ for all systems. Table I gives a summary of the counts measured in each collision system.

The physics quantity of interest here is the ratio of of the cross sections σ of the $\psi(2S)$ to $\psi(1S)$ mesons, multiplied by their respective branching ratio to dimuons $B_{\mu\mu}$. The counts N_{meas} of each meson are determined by the fits to the dimuon mass spectra, and are corrected for the PHENIX muon spectrometer pair acceptance Ω , pair detection efficiency ϵ , and dimuon trigger efficiency ϵ^{trig} for each species. The ratio of $\psi(2S)$ to $\psi(1S)$ mesons is given by

$$\frac{B_{\mu\mu}^{\psi(2S)} \sigma_{\psi(2S)}}{B_{\mu\mu}^{\psi(1S)} \sigma_{\psi(1S)}} = \frac{N_{\text{meas}}^{\psi(2S)}}{N_{\text{meas}}^{\psi(1S)}} \frac{\Omega_{\psi(1S)} \epsilon_{\psi(1S)}}{\Omega_{\psi(2S)} \epsilon_{\psi(2S)}} \frac{\epsilon_{\psi(1S)}^{\text{trig}}}{\epsilon_{\psi(2S)}^{\text{trig}}} \quad (1)$$

The acceptance \times efficiency factor $\frac{\Omega_{\psi(1S)} \epsilon_{\psi(1S)}}{\Omega_{\psi(2S)} \epsilon_{\psi(2S)}}$ is determined via a full GEANT4 simulation of the PHENIX detector [33]. A set of simulated dimuons, with a continuum of realistic mass, p_T , and rapidity distributions, is passed through the simulated PHENIX detector. The ratio of the acceptance \times efficiency at the $\psi(1S)$ mass value to the $\psi(2S)$ mass value is found to be ~ 0.8 for each arm. A systematic uncertainty on this factor is evaluated by changing the assumptions for the mass and p_T distributions of dimuons from the collisions. The relative dimuon

TABLE I. Summary of the measured ratios of $\psi(2S)/\psi(1S)$ mesons. The first (second) values in the rightmost column represent statistical (systematic) uncertainties.

Collision system	Rapidity interval	$N_{\text{meas}}^{\psi(1S)}$	$N_{\text{meas}}^{\psi(2S)}$	$\frac{B_{\mu\mu}^{\psi(2S)} \sigma_{\psi(2S)}}{B_{\mu\mu}^{\psi(1S)} \sigma_{\psi(1S)}} (\%)$
$p+p$	$1.2 < y < 2.2$	17120 ± 392	519 ± 51	$2.43 \pm 0.18 \pm 0.29$
$p+\text{Al}$	$1.2 < y < 2.2$ (p -going)	1497 ± 142	52 ± 11	$2.73 \pm 0.64 \pm 0.13$
$p+\text{Al}$	$-2.2 < y < -1.2$ (Al -going)	1463 ± 109	25 ± 11	$1.37 \pm 0.61 \pm 0.16$
$p+\text{Au}$	$1.2 < y < 2.2$ (p -going)	3893 ± 147	117 ± 18	$2.38 \pm 0.37 \pm 0.30$
$p+\text{Au}$	$-2.2 < y < -1.2$ (Au -going)	3561 ± 180	51 ± 18	$1.16 \pm 0.42 \pm 0.17$
$^3\text{He}+\text{Au}$	$1.2 < y < 2.2$ (^3He -going)	959 ± 64	27 ± 9.3	$2.24 \pm 0.78 \pm 0.32$
$^3\text{He}+\text{Au}$	$-2.2 < y < -1.2$ (Au -going)	1772 ± 132	35 ± 15	$1.59 \pm 0.67 \pm 0.60$

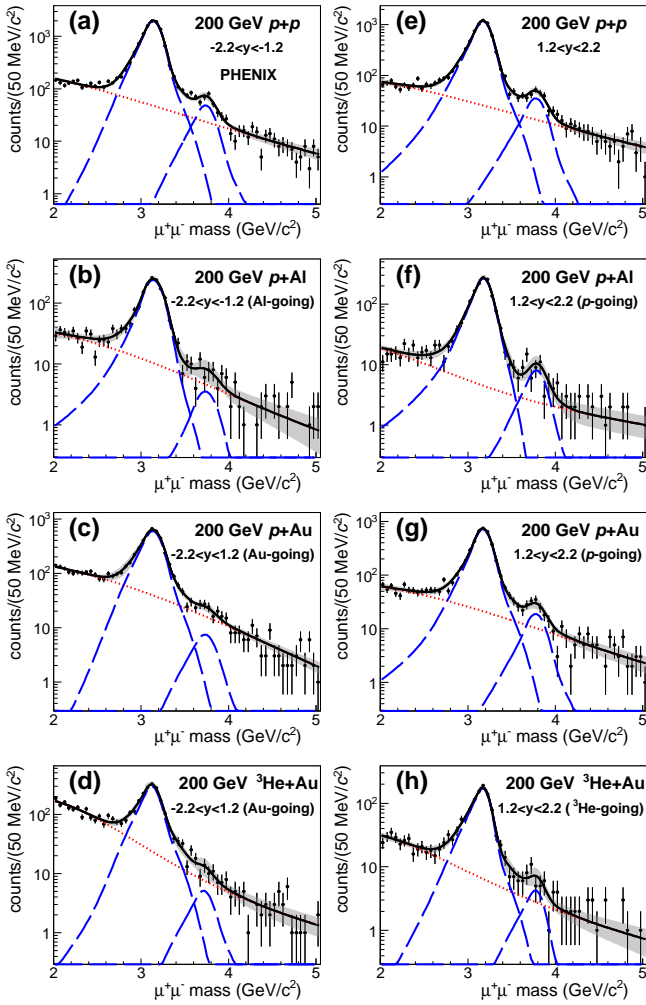


FIG. 1. The measured dimuon mass spectra with fits from the (a–d) South and (e–h) North PHENIX muon arms, for $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV. The total fit is the solid [black] line with a shaded [gray] band representing the 90% confidence level. The dashed [blue] and dotted [red] lines represent the contributions from the resonances and background, respectively.

trigger efficiency $\frac{\epsilon_{\psi(1S)}^{\text{trig}}}{\epsilon_{\psi(2S)}^{\text{trig}}}$ is measured by finding the proportion of dimuon pairs in the Minimum Bias triggered data set which also fire the dimuon trigger. This small correction factor is ~ 0.97 and is given a conservative relative systematic uncertainty of 1%. Because no significant $\psi(1S)$ polarization has been measured at PHENIX [34], all corrections are calculated under the assumption that the mesons are unpolarized.

IV. DISCUSSION

The p_T integrated ratios of $\psi(2S)$ to $\psi(1S)$ mesons extracted from the North and South spectrometer arms in the symmetric $p+p$ collision system agree within two standard deviations. These data points are averaged using statistical uncertainty weights. The resulting data point is shown in Fig. 2, and is consistent with world data taken at other collision energies. Little difference is observed in the ratio of $\psi(2S)$ to $\psi(1S)$ mesons produced in collisions with center-of-mass energies that range over nearly three orders of magnitude. This may imply that despite significant differences in the total charm cross section across these energies, once a precursor $c\bar{c}$ is produced, the probability that it will project onto a given charmonium state is insensitive to the conditions which formed the initial $c\bar{c}$ pair.

The same ratio is shown as a function of p_T in Fig. 3, along with a calculation based on a modified color evaporation model of charmonium production at 200 GeV [25]. This model factorizes the initial production of the $c\bar{c}$ pair from the color neutralization process via emission of soft gluons. The ratios reported here are somewhat higher than the model for $p_T > 2$ GeV/ c , but the data's limited statistical precision and significant theoretical error bands preclude any firm conclusions.

From Fig. 1 it is apparent that the $\psi(2S)$ peaks are suppressed relative to the $\psi(1S)$ peak in the columns on the left (in the A -going direction). Quantitative comparisons are accomplished by calculating the double ratio of $\psi(2S)/\psi(1S)$ production in $p/^3\text{He}+A$ collisions to the ratio found in $p+p$ collisions, as shown in Fig. 4. A

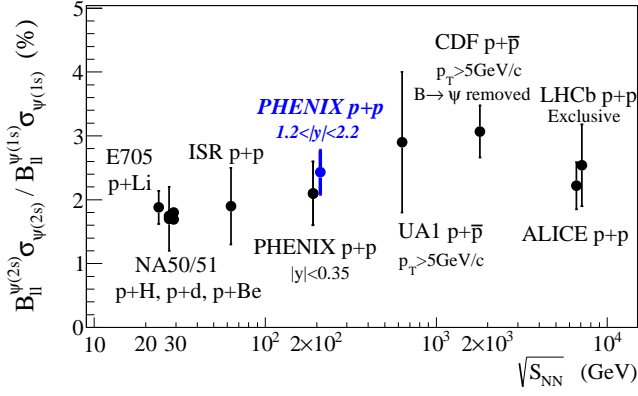


FIG. 2. Comparison of world data on the ratio of $\psi(2S)/\psi(1S)$ mesons in dilepton decays [21, 29, 35–41].

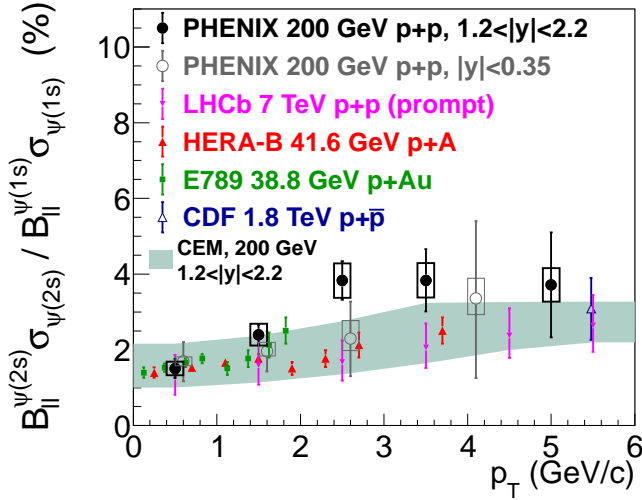


FIG. 3. Comparison of world data on the ratio of $\psi(2S)/\psi(1S)$ mesons as a function of p_T [29, 39, 42–44], along with a calculation from a color evaporation model (CEM) at $\sqrt{s}=200$ GeV [25].

previously published data point from midrapidity $d+Au$ collisions at the same energy is also included for comparison [23]. We see that at forward rapidity, the double ratio is consistent with unity in all three collision systems, indicating that any possible nuclear effects on the two charmonium states are comparable. Because these states are not fully formed until after they exit the nucleus, the fact that any nuclear effects have an equal magnitude on both states suggests that there are no significant final state effects on the pair which occur in this rapidity region.

At backward rapidity, the ratios in all collision systems are suppressed by a factor of ~ 2 . The mechanism for this preferential suppression of the $\psi(2S)$ relative to the $\psi(1S)$ is expected to occur after the $\psi(1S)$ formation time. A significant difference in the late stages of the

collision between this region and forward rapidity is the presence of a larger number of comoving hadrons (see [45] for measurements of the charged particle rapidity distributions in $d+Au$, a similar collision system). Once the $c\bar{c}$ pair exits the nucleus, it may be subject to interactions with these particles that can lead to breakup of the charmonium state, which are expected to be more pronounced on the less tightly bound $\psi(2S)$. While the exact nature of the interactions is not well understood, a model based on an absorption cross section that depends on the pair binding energy shows a preferential suppression that increases from forward to backward rapidity with comoving hadron multiplicity [46]. The model shows a similar trend with the $p+Au$ data, although it underestimates the relative suppression at backward rapidity (see the solid [black] line in Fig. 4). However, in $p+Al$, the model predicts almost no relative suppression at backward rapidity (dotted [red] line), while the data show a relative suppression similar to that in $p+Au$, within significant uncertainties.

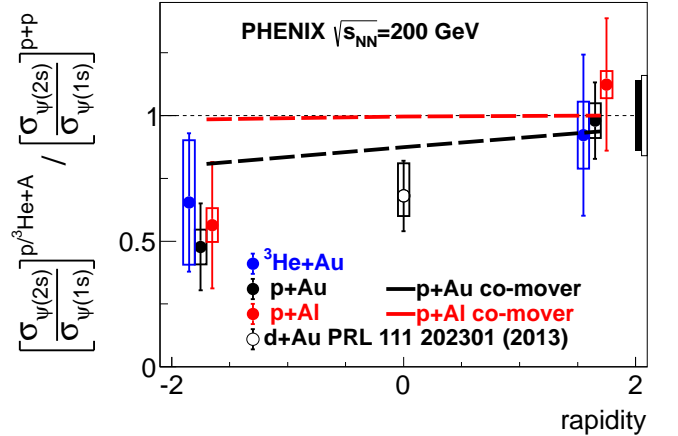


FIG. 4. The double ratio of $\psi(2S)/\psi(1S)$ mesons measured in $p/d/{}^3\text{He}+A$ collisions to that same ratio in $p+p$ collisions at $\sqrt{s}=200$ GeV, with a calculation based on breakup by comoving particles [46]. The bars (boxes) on the data points represent the statistical (systematic) uncertainties, and the shaded (open) box around unity represents the global uncertainty on the forward/backward (mid) rapidity data.

Measurements in 5.02 TeV $p+Pb$ collisions at the Large Hadron Collider (LHC) have also observed that the $\psi(2S)$ is preferentially suppressed compared to the $\psi(1S)$ [47, 48]. However, at this collision energy, the preferential suppression shows no significant rapidity dependence. This may indicate that the nuclear effects which preferentially suppress the $\psi(2S)$ are similar at forward and backward rapidity at the LHC. The charged particle pseudorapidity density per participant nucleon $(dN_{ch}/d\eta) / \langle N_{part} \rangle$ in $p+Pb$ collisions at the LHC was found to be almost twice as high as $d+Au$ collisions at RHIC [49], so interactions with comoving particles may be more significant, even at forward rapidity.

TABLE II. The charged particle multiplicity $dN_{ch}/d\eta$ determined from AMPT simulations [50, 51] and the nuclear overlap S_T from Loizides:2014vua simulations [52, 53] for the data shown in Fig. 5. Here we assume $dN/d\eta = \frac{3}{2}dN_{ch}/d\eta$, see text.

Collision system	$\sqrt{s_{NN}}$	Rapidity interval	$(dN_{ch}/d\eta)_{AMPT}$	$\langle S_T \rangle$ (fm ²)	$\frac{(dN/d\eta)_{AMPT}}{\langle S_T \rangle}$ (fm ⁻²)
$p+Al$	200 GeV	$-2.2 < y < -1.2$	5.9	0.82	10.8
$p+Al$	200 GeV	$1.2 < y < 2.2$	4.8	0.82	8.8
$p+Au$	200 GeV	$-2.2 < y < -1.2$	10.2	1.01	15.1
$p+Au$	200 GeV	$1.2 < y < 2.2$	6.5	1.01	9.7
^3He+Au	200 GeV	$-2.2 < y < -1.2$	20.3	2.35	13.0
^3He+Au	200 GeV	$1.2 < y < 2.2$	13.5	2.35	8.6
$p+Pb$	5.02 TeV	$-4.46 < y < -2.03$	19.9	1.3	23.0
$p+Pb$	5.02 TeV	$2.03 < y < 3.53$	15	1.3	17.3
$p+Pb$	5.02 TeV	$-4.0 < y < -2.5$	20.4	1.3	23.5
$p+Pb$	5.02 TeV	$2.5 < y < 4.0$	13.7	1.3	15.8

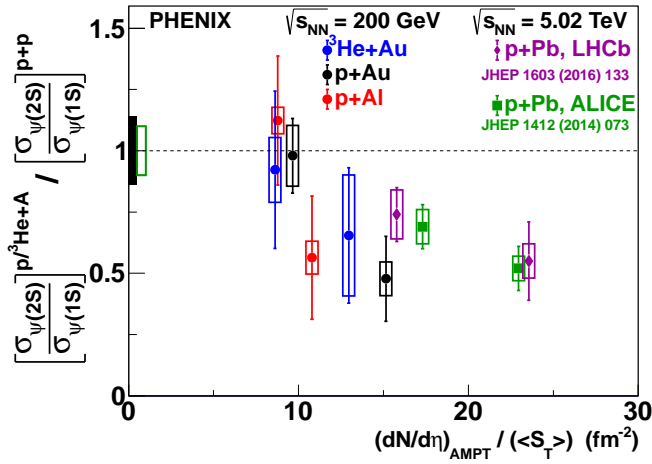


FIG. 5. The double ratio of $\psi(2S)/\psi(1S)$ mesons measured in $p/{}^3\text{He}+A$ collisions to that same ratio in $p+p$ collisions as a function of comoving particle density. The shaded [black] (open [green]) box around unity represents the global uncertainty on the PHENIX (ALICE) data.

For a direct comparison, the double ratios measured by PHENIX and at the LHC are plotted together in Fig. 5 as a function of comoving particle density, which is defined as the particle multiplicity $dN/d\eta$ divided by the nuclear overlap $\langle S_T \rangle$. As measurements of the particle multiplicity do not exist for all these systems, the charged particle multiplicity $dN_{ch}/d\eta$ is determined by AMPT simulations [50, 51] and multiplied by 3/2 to give the approximate total particle multiplicity $dN/d\eta$. The nuclear overlap $\langle S_T \rangle$ is defined as

$$\langle S_T \rangle = 4\pi \sqrt{\langle x^2 \rangle \langle y^2 \rangle - \langle xy \rangle^2} \quad (2)$$

where x and y are the spatial coordinates of the participating nucleons. This quantity is found via Monte Carlo Glauber simulations of the various collision species [52], with the ${}^3\text{He}$ geometry modified as described in Ref. [53].

Table II summarizes the results of these simulations.

Figure 5 shows that the double ratio decreases as the comoving particle density increases, which is qualitatively consistent with expectations of charmonium breakup through final state interactions. The forward-rapidity PHENIX data at relatively low comover density shows no preferential suppression of $\psi(2S)/\psi(1S)$, but the forward rapidity LHC data show a relative suppression that is comparable to the backward rapidity PHENIX data at similar comover density, within uncertainties. The backward LHC data, at the highest comover density, also shows relative suppression.

Understanding suppression due to comovers could play a critical role in interpreting quarkonia data from $A+A$ collisions. Existing data on excited charmonia states in $A+A$ collisions generally suffer from poor statistics, large combinatorial backgrounds, and cover limited p_T ranges [54, 55]. However, a clear sequential suppression of the excited bottomonium states has been observed in Pb+Pb collisions at the LHC [56]. While color screening is expected to play a role, given the high charged particle density in these collisions, it is reasonable to expect that similar breakup mechanisms can also have an effect on these states. In particular, the highly suppressed $\Upsilon(3S)$ state has a binding energy of only ~ 200 MeV, and may be especially sensitive to breakup through interactions with comoving particles.

V. CONCLUSIONS

In conclusion, we have found that the relative production of $\psi(2S)$ to $\psi(1S)$ mesons in $p+p$ collisions at $\sqrt{s} = 200$ GeV is consistent with expectations from a modified color evaporation model of charmonium production. In $p/{}^3\text{He}+A$ collisions at forward rapidity we observe no difference in the $\psi(2S)/\psi(1S)$ ratio relative to $p+p$ collisions, which indicates that any possible nuclear effects that are present in this rapidity region are common between the two states, and therefore appear to occur on

a timescale that is short compared to the charmonium formation time. At backward rapidity, where the comoving particle density is higher, we find that the $\psi(2S)$ is preferentially suppressed by a factor of ~ 2 . This effect is likely not due to any interaction in the nucleus, because the $c\bar{c}$ pair exits the nucleus before final meson formation occurs. The preferential suppression appears consistent with interactions of the fully formed color-neutral meson with comoving particles. The magnitude of this breakup mechanism is dependent on the meson binding energy, and is likely important for interpretation of sequential screening of quarkonia in $A+A$ collisions.

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